REPORT DOCUMENT PAGE

AFRL-SR-BL-TR-98-
0218

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
Dec. 29, 1997

3. REPORT TYPE AND DATES COVERED
Final Technical Report 9/1/93 to 8/31/97

4. TITLE AND SUBTITLE
Modeling the Mechanical Behavior of Aluminum Laminated Metal Composites During High Temperature Deformation

5. FUNDING NUMBERS
AFOSR Grant No.
F49 620-93-1-0466

6. AUTHORS
R. B. Grishaber, R. S. Mishra and A. K. Mukherjee

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Chemical Engineering & Materials Science
University of California
One Shields Avenue
Davis, CA 95616

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NC
110 Duncan Avenue, Suite B115
Bolling Air Force Base, DC 20332-001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited

19980311 088

BUTION CODE

13. ABSTRACT (Maximum 200 words) A constitutive model for deformation of a novel laminated metal composite (LMC) which is comprised of 21 alternating layers of Al 5182 alloy and Al 6090/SiC/25p metal matrix composite (MMC) has been proposed. The LMC as well as the constituent or neat structures have been deformed in uniaxial tension within a broad range of strain-rates (*i.e.* 10^{-6} to 10^{+1} s^{-1}) and moderate to high homologous temperatures (*i.e.* $0.3 \geq 0.95$ T_m). The LMC structure exhibits a behavior somewhat closer to the MMC layers. The results of these experiments have lead to a thorough characterization of the neat layer's mechanical behavior and a subsequent semi-empirical constitutive rate equation for both the Al 5182 and Al 6090/SiC/25p. These predictive relations for the neat layers have been coupled with a proposed model for deformation. This deformation model has led to the development of a constitutive relationship between flow stress and applied strain-rate for the laminated structure which has been compared with experimental data.

14. SUBJECT TERMS
Laminated Metal Composite, Mechanical Behavior, Modeling

15. NUMBER OF PAGES 21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

FINAL TECHNICAL REPORT

AFOSR GRANT NO.: F49620-93-1-0466

Period: 9/1/93 to 8/31/97

Prepared by

A. K. Mukherjee
Department of Chemical Engineering & Materials Science
University of California
One Shields Drive
Davis, CA 95616

December 29, 1997

MODELING THE MECHANICAL BEHAVIOR OF ALUMINUM LAMINATED METAL COMPOSITES DURING HIGH TEMPERATURE DEFORMATION

R.B. GRISHABER*, R.S. MISHRA AND A.K. MUKHERJEE
Department of Chemical Engineering and Material Science, University of California, Davis, California 95616, U.S.A.

*Now at W.L. Gore and Associates, Inc.
3450 W. Kiltie Lane, Flagstaff, Arizona 86002, U.S.A.

ABSTRACT

A constitutive model for deformation of a novel laminated metal composite (LMC) which is comprised of 21 alternating layers of Al 5182 alloy and Al 6090/SiC/25p metal matrix composite (MMC) has been proposed. The LMC as well as the constituent or neat structures have been deformed in uniaxial tension within a broad range of strain-rates (*i.e.* 10^{-6} to 10^{+1} s^{-1}) and moderate to high homologous temperatures (*i.e.* $0.3 \geq 0.95$ T_m). The stress exponent, n, of the Al 5182 layers increases from 3 to 5 with increasing strain-rate (*i.e.* $>10^{-3}$ s^{-1}). The MMC layer's apparent n value decreases from 7 to 5 with increasing temperature. Furthermore, at low strain-rates (*i.e.* $<10^{-3}$ s^{-1}) an apparent threshold stress dominates the MMC's observed mechanical behavior. The LMC structure exhibits a behavior somewhat closer to the MMC layers. The results of these experiments have lead to a thorough characterization of the neat layer's mechanical behavior and a subsequent semi-empirical constitutive rate equation for both the Al 5182 and Al 6090/SiC/25p. These predictive relations for the neat layers have been coupled with a proposed model which takes into account the dynamic load sharing between the elastically stiffer and softer layers when loaded axially during isostrain deformation of the LMC. This deformation model has led to the development of a constitutive relationship between flow stress and applied strain-rate for the laminated structure which has been compared with experimental data.

INTRODUCTION

Multi-layer laminate metal composites (LMCs), prepared by hot pressing alternate layers of the unreinforced and reinforced component materials and subsequent hot-rolling, can provide very attractive fracture toughness, damping capacity and also strength properties [1]. The influence of laminate architecture (layer thickness and component volume fraction) as well as component material properties and microstructural residual stress on toughening mechanisms and the resulting crack growth resistance are being actively studied [2, 3]. Interfaces in LMCs were observed to delaminate during the crack propagation leading to blunting [4, 5] or deflection [4, 6] of the crack.

One of the two monolithic (hereafter referred to as *neat*) layer materials of the LMC studied in this work is a discontinuously reinforced aluminum (DRA) alloy composite (also commonly referred to as metal matrix composites (MMCs)) whereas the other is a more conventional solid-solution strengthened aluminum (Al) alloy. Such DRA composites are typically reinforced by particles, whiskers or short fibers. They merit attention because of their desirable properties including low density, high specific stiffness, reduced coefficient of thermal expansion and increased fatigue resistance [7]. In many stiffness-, strength-, and weight-critical applications they can offer higher performance than traditional aluminum alloys at potentially lower cost than organic matrix composites [8]. DRA composites fabricated using elevated-temperature powder metallurgy based Al alloys are also attractive candidates for replacing higher cost titanium alloys in some applications [7].

Thus, the merit of this work is to characterize the mechanical behavior of Al-matrix LMCs as a function of temperature and loading conditions and to subsequently generate a micromechanistically predictive rate equation for correlating with the observed experimental data.

EXPERIMENT

The LMC of interest is comprised of 21 alternating diffusion-bonded Al layers of a 5182 (*i.e.* Al-5Mg, 11 layers) alloy and a 6090 Al-Mg-Si matrix with 25vol.% silicon carbide particulate (*i.e.* Al 6090/SiC/25p, 10 layers) ceramic-reinforced alloy as represented in figure 1. From this figure, the average linear intercept grain size within the Al-5Mg and Al 6090/SiC/25p layers of the LMC was determined to be 37. and 6. μm, respectably. The chemical constitution of each alloy was analyzed by use of a Cameca Instruments, Inc. SX-50 electron microprobe and is reported in table 1. Both of the neat alloys are commercially available. The Al-5Mg alloy is a wrought product whereas the Al 6090/SiC/25p (hereafter *MMC*) material is produced by a extruded powder metallurgy process. As seen in figure 2a for the as-received (*i.e.* prior to lamination) Al-5Mg neat material, the actual grain size distribution is most likely bimodal. However, the average linear intercept grain size was determined to be 28 μm. For the corresponding Al MMC neat material depicted in figure 2b, the average linear intercept matrix grain size was observed to be 6. μm. Also, the typical SiCp particulate diameter within the previous matrix was 7. μm. It should be noted that, in general, the reinforcement particulate distribution of the as-received Al MMC neat material was relatively inhomogeneously dispersed when observed in the long-transverse/short-transverse plane. The contiguous LMC is produced by hot pressing at a constant rate of deformation in an argon environment at 450°C (723K) to approximately a 12:1 reduction. Further reduction is completed by multipass hot rolling in air at 500°C (773K) with intermittent reheating to a final overall reduction ratio of approximately 15:1. The final sheet thickness of the LMC was approximately 1.2 mm with an average layer thickness of 62. μm. A final T6 (*i.e.* 180°C (453K) for 16-18 hours) heat treatment was carried out on the LMC to precipitation strengthen the Al MMC neat layers.

Uniaxial specimens were electrodischarge machined from the LMC sheet material materials with the rolling direction corresponding to the specimen's tensile axis. The uniaxial constant strain-rate (CSR) tests were conducted on a MTS model 312.12 100 kN platform with an integrated MTS 458 microprofiler ram controller. The microprofiler is preprogrammed prior to testing via a personal computer interface. The custom data acquisition and control software algorithm was designed to incrementally step up the ram velocity during uniaxial elongation to insure a constant strain-rate (CSR). A high temperature retort within a Research Incorporated radiant heat furnace was specially designed to allow for control of a desired testing environment. The tensile specimen was cleaned in acetone and dried in methanol prior to installation within the testing frame. The tests were conducted within a broad range of strain-rates (*i.e.* 10^{-6} to 10^{+1} s^{-1}) and moderate to high homologous temperatures (*i.e.* $0.3 \geq 0.95\ T_m$ where T_m is the melting point temperature) in flowing argon (containing an average of 10-15 ppm O_2) at a rate of 170 cc min^{-1} and pressure of 1.5 psig.

RESULTS

Evaluation of Constitutive Layers

Optimal forming or, conversely, creep resistant properties of the LMC can be *a priori* engineered into the desired structure provided a characterization of each neat layer's mechanical properties has been completed. Moreover, micromechanistic modeling of the LMC can be accomplished by use of the proper constitutive equations which reasonably predict the deformation response of each neat layers within an appropriate load sharing model. This particular section will focus on the critical evaluation procedures and results for characterization of the neat layers while the following subsections will concentrate on describing the constitutive equations for deformation of both the neat and laminate material systems.

Al-5Mg Neat Layer Characterization

The Al-5Mg alloy shows two distinct stress-strain-rate regimes as shown in figure 3. At low CSRs (*i.e.* 10^{-3} s^{-1}), a transition occurs from a solute-dislocation interaction (*i.e.* viscous creep) mechanism with a stress sensitivity exponent of 3 at the lower temperatures (*i.e.* around 470°C, 0.88 T_m) to an apparent Newtonian viscous rate controlling mechanism at a temperature much closer to the melting point of the matrix (*i.e.* 550°C, 0.98 T_m). The latter mechanism with a stress sensitivity value of 1 can be attributed to either diffusional creep [9-11], Harper-Dorn (HD) creep [12-14] or a recently discussed deformation phenomena of a Newtonian viscous interphase at the grain boundaries by Baudelet *et al.* [15, 16]. Further study will be required to positively isolate and determine the rate controlling deformation mechanism within this higher homologous temperature regime. However, for constitutive modeling purposes in this effort an appropriate Dorn constant will be selected, assuming a linear relationship between stress and strain-rate (*i.e.* $n = 1$).

The second regime occurs during transition from intermediate to high (*i.e.* 10^{-3} s^{-1}) applied CSRs, the rate controlling deformation mechanism of viscous creep changes to one of dislocation climb controlled creep at temperatures of 0.75 T_m and above. Correspondingly, the stress sensitivity exponent increases from a value of around 3 to 5. Similar investigations into this material system conducted recently by Lee *et al.* [17] and by other researchers [18-20], support these findings. In figure 4a, an Arrhenius rate plot of true strain-rate vs. the inverse of temperature shows that the experimentally determined activation energies of deformation for the low, 147 kJ mol^{-1}, and high, 153 kJ mol^{-1}, stress regions of Al-5Mg are both energetically similar to the value for Al lattice self-diffusivity, 142 kJ mol^{-1}. This equivalency is expected if viscous creep and dislocation climb controlled creep are rate-controlling in the intermediate

and high stress regions, respectively [21] (The more exact Darken diffusivity for viscous creep in Mg-atom locked dislocation glide is not available.).

Al 6090/SiC/25p Neat Layer Characterization

The apparent stress exponent, n, of the MMC neat material can be characterized as a transition from a value of 7 to 5 with increasing test temperature (*i.e.* 500°C, 0.88 T_m to 560°C, 0.95 T_m) within a CSR window of 10^{-2} to 10^{-1} s^{-1} as seen in figure 5. Furthermore, an apparent approach to a internal stress dominated deformation condition was observed at higher test temperatures and relatively low applied CSRs (*i.e.* 10^{-2} s^{-1}). Also, in figure 4b, the apparent activation energy for deformation was determined from a typical Arrhenius plot with a value of approximately 356 kJ mol^{-1}. This value is simply too high for any diffusion-related correlation in an aluminum matrix. Thus, in order to constitutively model the mechanical behavior of the MMC, the true mechanistic information must be isolated from the apparent stress sensitivity exponents and also the apparent activation energy of deformation by removing the effects related to the internal stress state. The numerical and experimental procedures of such a process have been addressed by Pandey et al. [22].

Using this methodology, the true stress sensitivity exponent was determined to have a magnitude of 3 indicative of a rate controlling viscous creep deformation mechanism. This conclusion was substantiated with TEM results where significant intragranular dislocation activity was observed and there was no evidence of subgrains. Moreover, the true activation energy for deformation, which was obtained by reanalyzing the primary data in terms of an effective stress (*i.e.* the applied stress minus the structure dependent back stress), was determined to be equal to 156 kJ mol^{-1} which compares favorably with that reported in the previous section for Al self-diffusivity. This conclusion also supports viscous creep as being the operative rate controlling mechanism within the Al MMC neat layers.

Modeling High Temperature Deformation

This section will concentrate on discussing the necessary constitutive equations which govern the deformation behavior of the neat materials as well as that of the laminated structure. At relatively high homologous temperatures, typically above 0.5 T_m, the rate of deformation as a function of applied stress, σ, can be expressed, as a function of the strain rate, $\dot{\varepsilon}$, as:

$$\dot{\varepsilon} \propto (\sigma)^n \qquad (1)$$

which is the basis for power-law controlled creep or deformation where n is the stress sensitivity exponent. Mukherjee *et al.* [23] used this proportionality to advance the accepted semi-empirical constitutive equation for power-law deformation, as follows:

$$\dot{\varepsilon} = A\left(\frac{GbD_o}{kT}\right)\left(\frac{\sigma}{G}\right)^n\left(\frac{b}{d}\right)^p \exp\left(\frac{-Q}{RT}\right) \qquad (2)$$

where G is temperature sensitive shear modulus, b the Burger's vector, Do is the pre-exponential diffusivity term, k is Boltzmann's constant, T is the absolute temperature, d is the linear grain size, p is the grain size exponent, Q is the apparent activation energy for deformation, R is the universal gas constant and A is the mechanism dependent structure constant.

The validity of using Eqn. 2 as a predictive constitutive equation has been addressed elsewhere [24-26]. Moreover, it is accepted that the magnitude of the apparent activation energy for deformation, Q, will be equivalent to the activation energy for either self-diffusivity of atoms along the grain boundaries or through the lattice depending on the specific micromechanism. Correspondingly, if micrograin superplasticity is operative, then the grain size exponent, p, will typically correlate ranging from 3 to 2, depending upon whether grain boundary or lattice diffusivity is rate controlling, respectably. For dislocation climb controlled

creep or viscous glide (*i.e.* alloy) creep, the p exponent in eqn. 2 is typically accepted to have a value of zero.

A modified version of eqn. 2, using the concept of an effective stress, was put forth by Ashby and Verrall [27] to explain results regarding an apparent threshold stress which acts to resist deformation due to the applied stress during diffusionally accommodated superplastic flow. Thus, the effective stress, σ_{eff}, can be given as:

$$\sigma_{eff} = (\sigma_a - \sigma_o) \tag{3}$$

where σ_a is the applied stress and the σ_o is the threshold stress. A concise discussion in regards to the nature and origin of the threshold stress has been put forth in a review by Gibeling and Nix [28]. Note that the determination of the threshold stress, σ_o, in eqn. 3 can be determined by a numerical extrapolation method originally prescribed by Lagneborg [29] and later advanced by Mohamed [30]. Thus, by replacing σ in eqn. 2 with σ_{eff} from eqn. 3, the resultant constitutive equation is, as follows:

$$\dot{\varepsilon} = A\left(\frac{GbD_o}{kT}\right)\left(\frac{\sigma - \sigma_o}{G}\right)^n \left(\frac{b}{d}\right)^p \exp\left(\frac{-Q}{RT}\right) \tag{4}$$

This constitutive relationship has been shown to predict reasonably the mechanical behavior of dispersion-strengthened materials [22, 31-33] within the power-law creep controlled deformation region. The method of using effective stress values rather than applied stress values when an apparent threshold stress is determined to be significant aides in determining realistic activation energies and stress exponent values [34]. The recent works of Bieler *et al.* [35] and an overview by Mishra *et al.* [36] have shed significantly more information on this particular area.

Constitutive Modeling of Laminated Metal Composites

Using the results and constitutive relations previously discussed, the primary focus of this section will be to present a theoretical model for micromechanistically predicting the response to an applied stress by the laminated structure. First, the following assumptions will be considered:

a) the laminated structure will be loaded such that the all of the individual layers are acted upon by an applied force in a parallel configuration,

b) isostrain and correspondingly isostrain-rate conditions will apply continuously throughout the entire deformation process,

c) load sharing to maintain the previous assumption will occur within the LMC where the elastically stiffer layers will accumulate a larger portion of the total applied load in order to maintain strain compatibility,

d) the initial volume fractions of each neat phase within the deforming gage volume will not vary as a function of strain accumulation.

Thus, given the above set of limits, it would be reasonable to expect that a LMC would exhibit a rule-of-mixtures or weighted average effect of mechanical behavior attributed to that associated with each neat layer under similar deformation conditions. This can be visualized by considering the issue of strain compatibility where the elastically stiffer layer will accumulate a greater share of the overall applied load. If however, the flow stress in either laminate layer are similar at a given applied strain rate, then high stress concentrations in the stiffer layer or phase will tend to be relaxed. Thus, the tendency for premature failure due to stress assisted cavitation will be lessened, as addressed in depth by Kashyap and Mukherjee [37] as well as by others [38, 39].

By considering the laminate layers as two separate phases of the composite structure loaded axially, it is expected that the operative rate controlling mechanism is equivalent to that determined for its monolithic component deformed under identical conditions. Therefore, using principles discussed in a review by Lilholt [40] for load sharing and correspondingly stress sharing under elastically loaded isostrain conditions, the stress of the composite, σ_{LMC}, can be written as:

$$\sigma_{LMC} = (V \cdot \sigma)\big|_{alloy} + (V \cdot \sigma)\big|_{MMC} \tag{5}$$

The volume fractions of the neat layers which correspond to the elastically softer and elastically stiffer (*i.e.* V_{alloy} and V_{MMC}, respectively) are representative of the entire LMC and given as:

$$V_{alloy} + V_{MMC} = 1 \tag{6}$$

In figure 6, a schematic representation of this model is presented. The approach to modeling the deformation behavior of the LMC is similar to that originally presented by McDanels [41] for creep of an unidirectional continuous-fiber composite and later advanced by Kelly and Street [42, 43] and more recently by Goto and McClean [44-46]. The composite model considered in this treatment is similar to the condition where both the reinforced fibers and the matrix phase deform by power-law creep. We consider the reinforcement fibers in the previous models to be equivalent to the MMC layers of our prototype LMC. As shown in figure 7, the response of the laminated structure to an applied constant strain-rate can be modeled with eqn. 5 using the constitutive predictions of the alloy and MMC neat structures under independent and identical conditions from eqn.s 2 and 4, respectively. The constitutive predictions for the deformation response of the LMC and the two neat materials at both 490°C and 550°C are presented in this figure with experimental results. From this figure, it is clearly evident that the isostrain model presented in this work can be used to reasonably and

constitutively predict the high temperature mechanical behavior of Al-matrix laminated metal composites.

CONCLUSIONS

By *a priori* characterization of the high temperature mechanical behavior of the individual layer materials which comprise the laminated structure of interest, a model which accounts for load sharing between the elastically stiffer and softer layers during isostrain deformation has been presented and experimentally verified.

ACKNOWLEDGMENTS

This work is supported by grant no. F49620-93-1-0466 from the Department of Defense (DOD) Air Force Office of Scientific Research (AFOSR) under the auspices of Dr. Charles H. Ward, Capt. USAF, Bolling AFB, DC. The authors would also like to especially acknowledge Dr. Donald R. Lesuer and Dr. Chol K. Syn of Lawrence Livermore National Laboratory in California for providing the material used in this work.

REFERENCES

1. C. K. Syn, D. R. Lesuer and O. D. Sherby in Light Materials for Transportation Systems, ed. N. J. Kim, (Center for Advanced Aerospace Materials, Kyongju, Korea, 1993), p. 763.
2. D. Lesuer, C. Syn, R. Riddle, O. Sherby, to be published in Symposium on Intrinsic and Extrinsic Fracture Mechanisms in Discontinuously Reinforced Inorganic Composite Systems (TMS Meeting, Las Vegas, NV, 1995).
3. M. Manoharan, L. Ellis, J. J. Lewandowski, Scripta Met. et Mater., **24**, 1515 (1990).
4. R. O. Ritchi, W. Yu, and R. J. Bucci, Eng. Fract. Mechanics, **32**, 362 (1989).
5. C. K. Syn, S. Stoner, D. R. Lesuer, O. D. Sherby, to be published in Symposium on High Performance Ceramic & Metal Matrix Composites (TMS Meeting, San Francisco, CA, 1994).
6. T. M. Osman, M. S. Thesis, Case Western Reserve University, 1993.
7. W. H. Hunt, T. M. Osman and J. J. Lewandowski, J.O.M., **45**, 30 (1993).
8. M. B. McKimpson, E. L. Pohlenz and S. R. Thompson, J.O.M., **45**, 26 (1993).
9. F. R. N. Nabarro, Rep. Conf. Strength Solids, 1948, 75-90.
10. C. Herring, Applied Physics, **21**, 437 (1950).
11. R. L. Coble, Applied Physics, **34**, 1679 (1963).
12. J. Harper and J. E. Dorn, Acta Metall., **5**, 654 (1957).
13. J. Fiala and T. G. Langdon, Mater. Sci. Engr., **A151**, 147 (1992).

14. O. A. Ruano, J. Wolfenstine, J. Wadsworth and O. D. Sherby, Acta Metall., **39**, 661 (1991).
15. B. Baudelet, M. C. Dang, F. Bourdeaux, Scripta Metall. Mater., **26**, 573 (1992).
16. B. Baudelet and M. C. Dang in Adv. Materials '93, III/B: Composites, Grain Boundaries and Nanophase Materials , eds. M. Sakai, M. Kobayashi, T. Suga, R. Wanatabe, Y. Ishida and K. Nihara, (Trans. Mat. Res. Soc. Jpn., **16B**, 1994) pp. 941-946.
17. D. H. Lee, K. T. Hong, D. H. Shin and S. W. Nam, Mater. Sci. Engr., **A156**, 43 (1992).
18. M. J. Mills, J. C. Gibeling and W. D. Nix, Acta Metall., **33**, 1503 (1985).
19. H. Oikawa and T. G. Langdon in Creep Behavior of Crystalline Solids, eds. B. Wilshire and R. W. Evans, Vol. 3, 33-82 (1984).
20. K. L. Murty, F. A. Mohamed and J. E. Dorn, Acta Metall., **20**, 1009 (1972).
21. A. K. Mukherjee in Materials Science and Technology, eds. R. W. Cahn, P. Haasen and E. J. Kramer, vol. ed. H. Mughrabi, (VCH, **6**, 1993) pp. 407-460.
22. A. B. Pandey, R. S. Mishra and Y. R. Mahatan, Scripta Metall., **24**, 1565 (1990).
23. A. K. Mukherjee, J. E. Bird and J. E. Dorn, Trans. ASM, **62**, 155 (1969).
24. A. K. Mukherjee in Treatise on Materials Science and Technology, ed. R. J. Arsenault, Vol. 6, 163 (1975).
25. O. D. Sherby and J. Wadsworth in Progress in Materials Science, Vol. 33, 169 (1989).
26. H. J. Frost and M. F. Ashby, Deformation-Mechanism Maps (Pergamon Press, Oxford, 1982), p. 12.
27. M. F. Ashby and R. A. Verrall, Acta Metall., **21**, 149 (1973).
28. J. C. Gibeling and W. D. Nix, Mater. Sci. Engr., **45**, 123 (1980).
29. R. Lagneborg, Scripta Metall., **7**, 605 (1973).
30. F. A. Mohamed, Jrn. Mat. Sci., **18**, 582 (1983).
31. E. Arzt, Res. Mechanica, **31**, 421 (1991).
32. G. Gonzalez-Doncel and O. D. Sherby, Acta Metall., **41**, 2797 (1993).
33. R. S. Mishra, A. G. Paradkar and K. N. Rao, Acta Metall., **41**, 2243 (1993).
34. R. S. Mishra and A. K. Mukherjee, Scripta Metall., **25**, 271 (1991).
35. T. R. Bieler, R. S. Mishra and A. K. Mukherjee in Materials Science Forums, Vols. 170-172, 65 (1994).
36. R. S. Mishra, T. R. Bieler and A. K. Mukherjee, Acta Metall. Mater., **43**, 877 (1995).
37. B. P. Kashyap and A. K. Mukherjee, Res Meachanica, **17**, 292 (1986).
38. K. Higashi and M. Mabuchi, Mater. Sci. Engr., **A176**, 461 (1994).
49. A. H. Chokshi and A. K. Mukherjee, Acta Metall., **37**, 3007 (1989).
40. H. Lilholt in Mechanical Properties of Metallic Composites, ed. S. Ochiai (Marcel Dekker, Inc., NY, 1994), pp. 389-471.
41. D. McDanels, R. A. Signorelli and J. W. Weeton, NASA Report TN-4173 (1967).
42. A. Kelly and K. N. Street, Proc. R. Soc., **A328**, 267 (1972a).
43. A. Kelly and K. N. Street, Proc. R. Soc., **A328**, 283 (1972b).
44. S. Goto and M. McClean, Scripta Metall., **23**, 2073 (1989).
45. S. Goto and M. McClean, Acta Metall., **39**, 153 (1991).
46. S. Goto and M. McClean, Acta Metall., **39**, 165 (1991).

LIST OF FIGURES

TABLES

Table 1. Neat Layer Chemical Composition.

Element	Al 5182 {Al-5Mg} (wt.%) ± 0.005	Al 6090/SiC/25p {MMC} (wt.%) ± 0.005
Mg	5.245	0.480
Si	0.018	1.620
Cr	0.030	0.150
Mn	0.285	0.025
Fe	0.030	0.785
Cu	0.025	0.340
Zn	Below MDL	Below MDL
Al	Balance	Balance

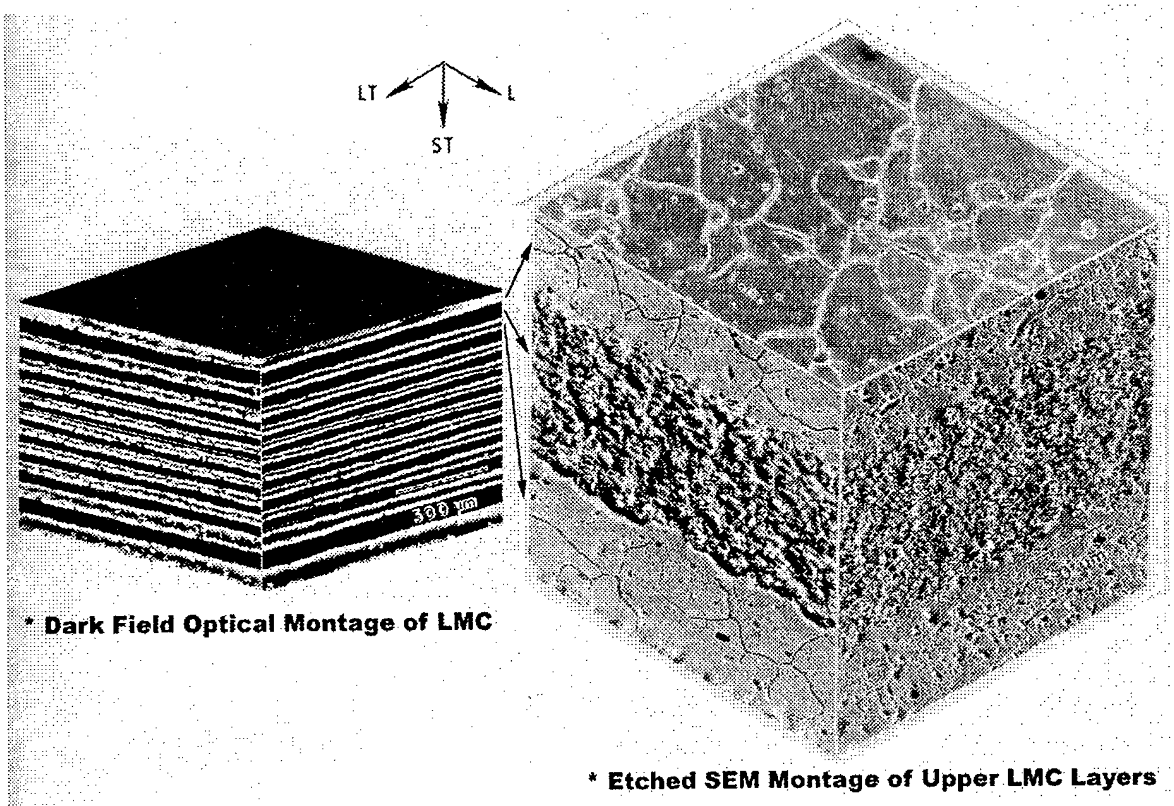

Figure 1. Representation of LMC Microstructure.

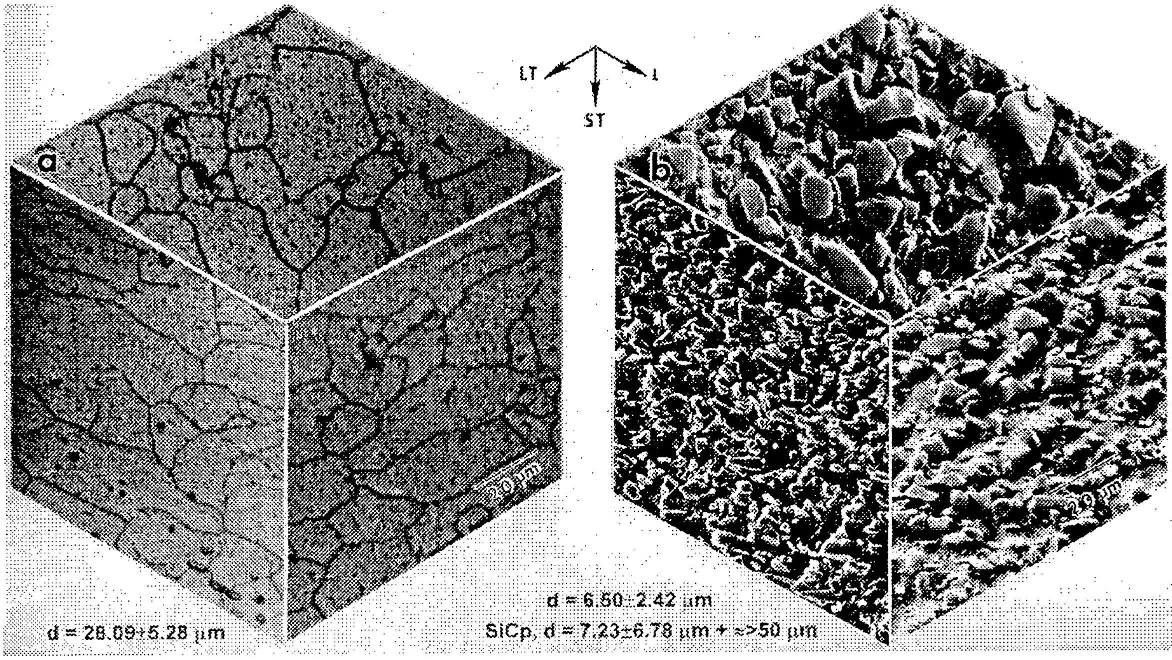

Figure 2. Neat Microstructures for a.) Al-5Mg and b.) Al MMC Layer Materials.

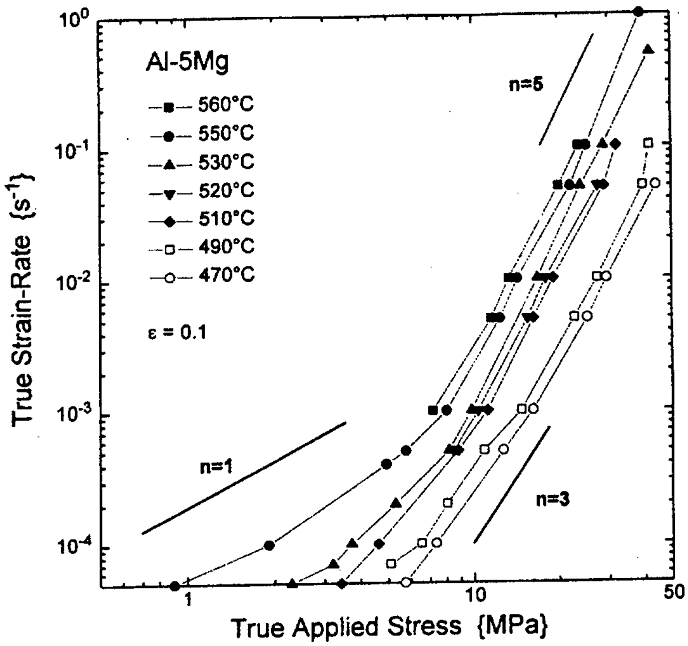

Figure 3. Strain-rate vs. Stress Response of Al-5Mg.

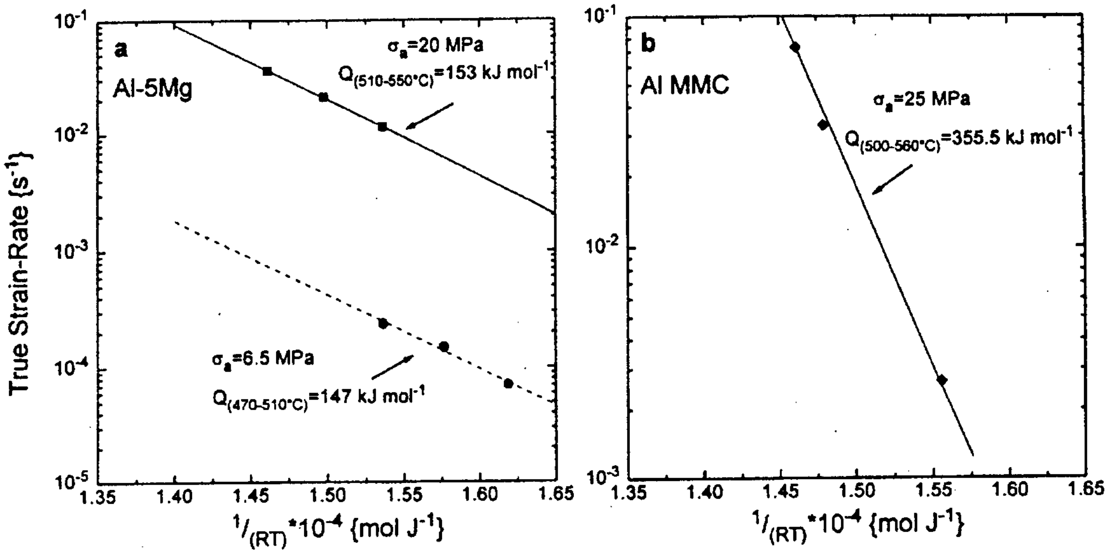

Figure 4. Arrhenius Plots to Determine Apparent Activation Energies of the a.) Al-5Mg and b.) Al MMC Neat Materials.

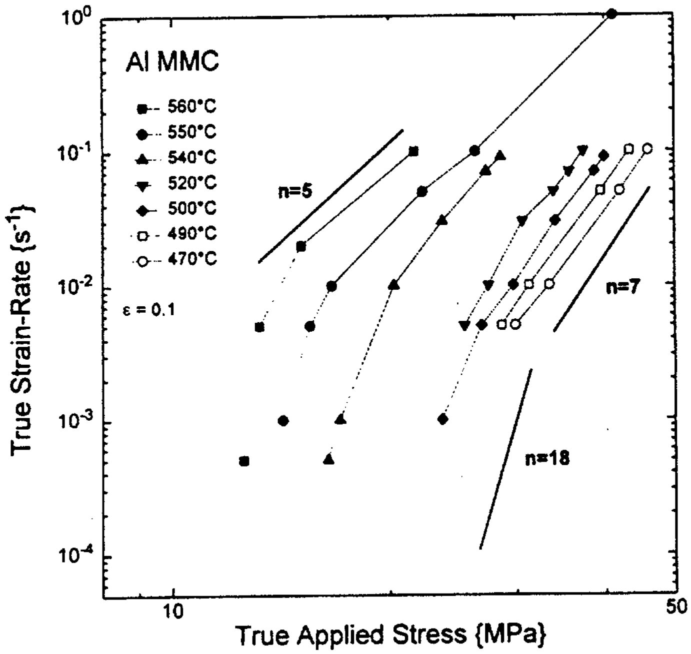

Figure 5. Strain-rate vs. Stress Response of Al 6090/SiC/25p

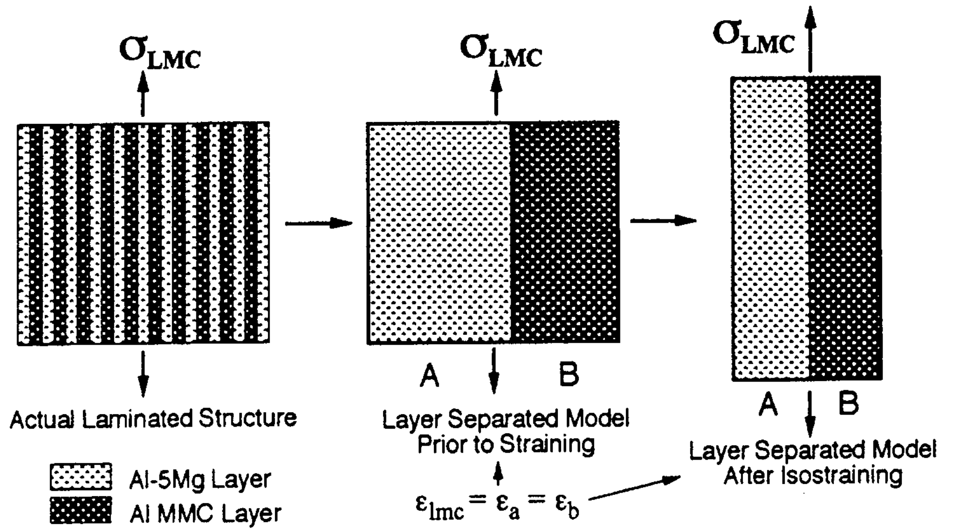

Figure 6. Schematic Model of Isostrain Loading Configuration for the Laminate.

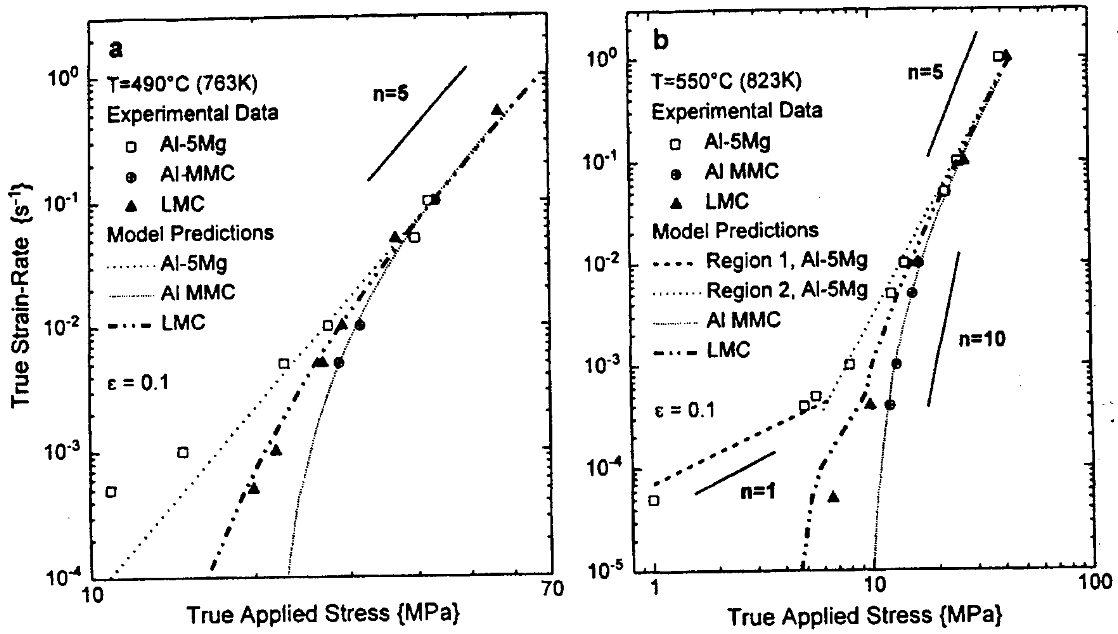

Figure 7. Deformation Modeling of the LMC using the Constitutive Relations for the Neat Materials Deformed Under Equivalent Conditions and the Load Sharing Model at a.) 490°C and b.) 550°C.